Proximity Charge Sensing With Semiconductor Detectors

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Abstract—Semiconductor radiation detectors are routinely used for the detection, imaging, and spectroscopy of gamma-ray, x-ray, and charged particles. In basic form, a detector is comprised of a semiconductor crystal with two or more electrodes formed on its surfaces. Besides allowing for the application of bias voltage, one or more of the electrodes on a detector also serve as readout electrode. Charge carriers drifting across the detector induce a charge signal on the electrode, which can then be measured by a charge-sensitive amplifier connected to the electrode. Although in general the readout electrodes of a detector are formed on the detector itself, charge can be induced on any electrode, even if the electrode is not physically in contact with the semiconductor. Such proximity charge sensing effects can be utilized to achieve a variety of advantages in applications involving semiconductor detectors. In this paper, we report on the experimental verification of signal readout using proximity electrodes and demonstrate several possible applications of this technique, including the position-sensitive readout of detectors and the sensing of incomplete charge collection in detectors as a means to reduce spectral background.

Index Terms—Charge sensing, imaging detectors, position-sensitive detectors, semiconductor detectors.

I. Introduction

SEMICONDUCTOR radiation detectors are routinely used for the detection, imaging and spectroscopy of gamma-ray, x-ray, and charged particles. In basic form, a detector is comprised of a semiconductor crystal with two or more electrodes formed on its surfaces. Besides allowing for the application of bias voltage, one or more of the electrodes on a detector also serve as readout electrode. Charge carriers drifting across the detector induce a charge signal on the electrode, which can then be measured by a charge-sensitive amplifier connected to the electrode. Although in general the readout electrodes of a detector are formed on the detector itself, charge can be induced on any electrode, even if the electrode is not physically in contact with the semiconductor.

Such proximity charge sensing effects have been utilized in gas ionization detectors [1], [2], and for edge compensation in CdZnTe coplanar-grid detectors [3]. The authors are not aware of any other published reports on the use of external electrodes for direct signal readout with semiconductor detectors. In this paper we discuss the principle of proximity charge sensing for semiconductor detectors, and demonstrate the use of this technique for non-contact position-sensitive readout of detectors, and the sensing of incomplete charge collection in detectors as a means to reduce spectral background.

II. Proximity Charge Sensing

The charge signal induced at an electrode due to the movement of a charge carrier in a detector is given by the Shockley-Ramo theorem [4], [5], and it can be calculated using the weighting potential method:

$$dQ_{ind} = -Q\, dV_w$$

Where Q_{ind} is the induced charge on the electrode, Q is the charge of the carriers, V_w is the weighting potential of the electrode. V_w is a dimensionless quantity that can be calculated using Poisson's equation by setting the space charge to zero and the potential of the electrode to unity with all other electrodes at zero potential. The dielectric of the detector material and of the surrounding materials must be included in the calculation to provide valid results. This method of induced signal calculation applies to any conductive electrode, provided that the electrode is maintained at a fixed potential (i.e., not floating).

According to the equation, as long as a non-zero weighting potential of the electrode exists inside a semiconductor detector where the charge movement occurs, a charge signal will be induced even if the electrode is not in contact with the detector. Fig. 1(a) shows an example detector configuration consisting of a detector crystal 2 cm × 2 cm in area and 1 cm thick, with a full area electrode on the bottom surface and a guard ring electrode on the top. The guard ring electrode has a 1.4 cm × 1.4 cm opening in the center. A separate 1 cm × 1 cm electrode (proximity electrode) is suspended 0.5 mm from the top surface of the detector and centered with respect to the opening in the guard ring electrode. Fig. 1(b) shows the calculated weighting potential of the proximity electrode along a vertical plane through the center of the detector. A dielectric constant of 12 was assumed for the detector crystal, and the surrounding medium was assumed to be air or vacuum with a dielectric constant of 1. The weighting potential drops off away from the electrode, and has a discontinuous slope upon entering the detector due to the change in dielectric constant. If charge carriers are collected onto the surface beneath the electrode, the total amount of charge induced on the electrode will be the initial charge generated in the detector multiplied by the weighting potential of the electrode at the collection point of the carriers, assuming there is no bulk trapping of the carriers, and the opposite polarity charge carriers are fully collected to the other contact(s) of the detector. The magnitude of the proximity electrode's weighting potential
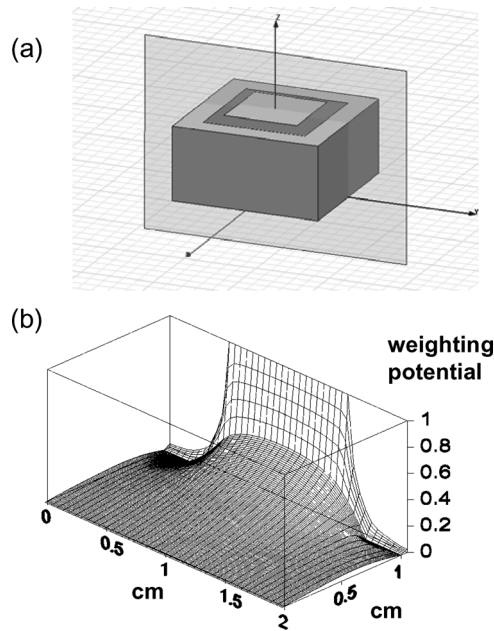
Fig. 1. (a) Geometry of the detector for the simulation, with the center proximity electrode at 0.5 mm above the detector surface. (b) Calculated weighting potential of the proximity electrode along a vertical plane through the center of the detector, as shown in (a).

Fig. 2. Non-contact readout of a detector using proximity electrodes.

at the detector surface is largely a function of the gap distance in relation to the detector thickness and the dielectric constant of the detector material. Since most semiconductor detector materials have fairly high dielectric constants (typically >10), a small gap is needed to ensure a large induced signal.

In the following, we will discuss and demonstrate experimentally two possible applications of such proximity charge sensing effect.

III. NON-CONTACT DETECTOR READOUT

Pixel and strip detectors are widely used to provide particle tracking and imaging capability for a wide variety of applications, including high-energy and nuclear physics, astronomy, medical imaging, and nuclear materials detection. Typically these detectors are fabricated by segmenting the electrode on one or both sides of the device. Electrical connections are then needed to connect each electrode element to the readout electronics. This is typically accomplished using wire bonding or bump bonding techniques. There are considerable complexities and costs associated with these interconnect technologies, especially for bump bonding. In addition, these bonding techniques may be difficult to apply for some semiconductor materials due to the poor mechanical strength of the materials or their inability to withstand high temperature processing. Also, bump bonding to cryogenic detectors, such as Ge, could be problematic due to differential thermal contraction between the detector and the readout board or ASIC. A non-contact readout technique could eliminate the need for such hard-wired interconnections and avoid much of the complexity and cost.

Fig. 2 illustrates a possible scheme to realize a non-contact readout pixel or strip detector using proximity charge sensing.
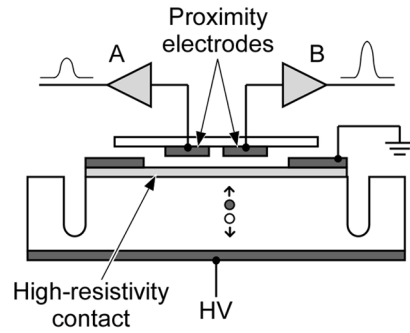
The detector is a simple planar device with two full-area contacts. Proximity readout electrodes are placed above a detector surface. The detector's contact adjacent to the proximity electrodes must satisfy two competing requirements. It has to be transparent to electric fields at the time scale comparable to the charge collection time of the readout electronics, so that a moving charge inside the detector can induce a signal on the proximity electrodes. At the same time, it has to allow signal carriers and leakage current collected at the contact to dissipate without excessive charge build up, which would otherwise distort the electric field in the detector. These requirements can be met by using a resistive contact with an appropriate sheet resistivity [6]. Additionally, the resistive contact has to function well as a blocking or ohmic contact depending on the requirements particular to the semiconductor material and application.

For detectors with low leakage currents, such as liquid-nitrogen-cooled Ge detectors, which typically have leakage currents $\ll 1$ nA, an electrode with sheet resistivity of $\sim 10^9$ ohm/$\square$ would be appropriate. The dissipation time for carriers collected at the electrode will be roughly equal to the RC time constant associated with the resistance of the electrode and the capacitance of the detector. For typical detector capacitances of ~ 10 pF and resistance $\sim 10^9$ ohm, the time constant would be ~ 10 ms, which is much longer than the typical pulse processing time for such detectors (several μs). Detectors with higher leakage currents, such as room-temperature-operated Si detectors and some compound semiconductor detectors (e.g., CdTe, CdZnTe, GaAs), may require a lower resistivity electrode to avoid charge buildup and distortion of the electric field. The lower resistivity would result in a smaller charge dissipation time constant, and a correspondingly shorter pulse shaping time would be required. This is not seen as a major issue, since a short shaping time is normally desired in such cases to reduce the noise contribution of high leakage currents. The tradeoffs in the selection of sheet resistivity of the contact are similar to the choice of the resistance of the feedback resistor in a DC-coupled charge-sensitive preamplifier. The amorphous Si and amorphous Ge contacts that we have developed for Si [7] and Ge [8] detectors can be tailored to have a wide range of resistivity, and they are thus well suited as resistive contacts for this application.

The non-contact proximity readout scheme simplifies detector fabrication since it is not necessary to produce segmented
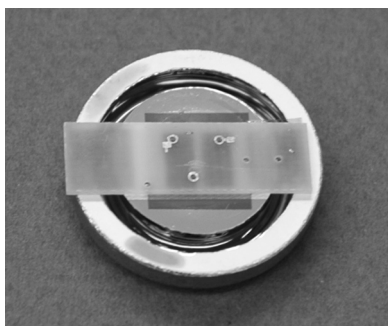
Fig. 3. Si(Li) detector used to demonstrate non-contact readout with proximity electrodes.
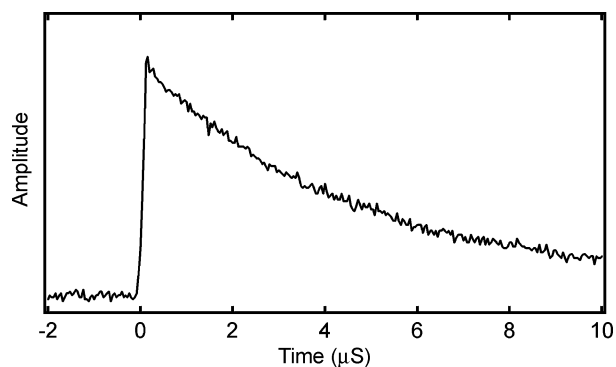

Fig. 4. Alpha particle signal from the charge-sensitive preamplifier connected to one of the proximity electrode for the detector in Fig. 3.
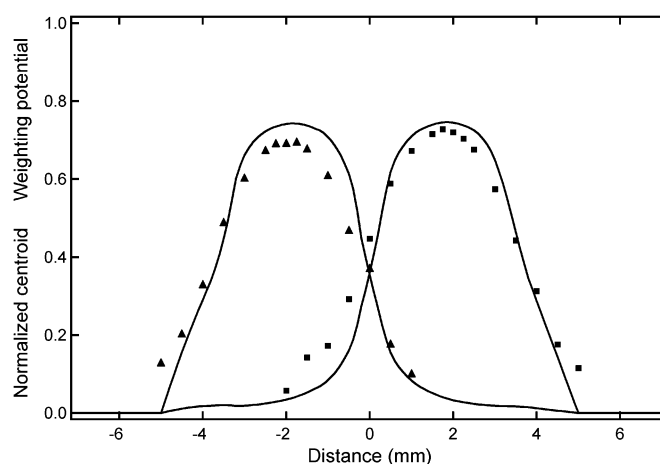

Fig. 5. Alpha particle scan of the Si(Li) detector with two proximity electrodes. The data points are the centroids of the alpha peaks at different positions. The curves are the calculated weighting potentials of the two electrodes at the detector surface.

electrode structures on the detectors themselves. Different segmentation schemes can be effectively implemented on the same detector by simply changing the geometry of the proximity readout electrodes.

Another advantage of the proximity readout scheme is the ability to perform signal interpolation to achieve a finer position resolution than that given by the pitch of the readout electrodes. The charge induced on a proximity electrode is determined by the weighting potential of the electrode at the point where the carriers are collected on the resistive electrode. By taking the ratios of the amplitudes of the induced signals on adjacent electrodes, the location of the collection point between the electrodes can be uniquely determined. Furthermore, once the location is determined, the loss in induced charge resulting from the weighting potential being less than 1 can be corrected in post processing to restore the full-energy signal and thus the spectroscopic performance of the detector. The above discussion assumes there is no significant trapping of carriers in the detector. If trapping is substantial, the schemes for position interpolation and signal correction may differ and be more complicated.

We used a 5 mm thick Si(Li) detector to demonstrate the non-contact readout scheme with proximity electrodes. The detector and readout geometry are similar to that shown in Fig. 2. A photograph of the detector and the proximity electrodes is shown in Fig. 3. The detector's original Li-diffused contact was removed after Li drifting and replaced with an amorphous-Si (a-Si) contact formed by RF sputtering [7]. The a-Si contact has a sheet resistivity of $\sim 10^7$ ohm/$\square$. Aluminum was evaporated over the a-Si contact except for a 10 mm $\times$ 10 mm area in the center. The Al layer serves as a conductive ring to allow the application of bias voltage to the a-Si contact. For our measurement, the a-Si contact was held at ground potential and a negative high-voltage bias was applied to the bottom contact, which is a standard Au surface barrier. A circuit board with two pad electrodes was held over the 10 mm $\times$ 10 mm opening to serve as the proximity electrodes. Each pad electrode has dimensions of 2.9 mm $\times$ 6 mm, and they are separated by a gap of 0.75 mm. The gap between the pads and the a-Si contact was about 60 μm. Each electrode was connected to a charge-sensitive preamplifier followed by a shaping amplifier. The detector was operated at room temperature.

The detector was tested by scanning a collimated alpha particle source along the bottom contact. Fig. 4 shows the signal

output from one of the charge sensitive preamplifiers in response to an alpha particle. The sharp rise of the signal corresponds to the drift of carriers across the detector, and the following decay is due to the dissipation of the carriers away from the collection point towards the guard ring. The decay time is approximately 6 μs, which is roughly as expected based on the sheet resistivity of the a-Si contact.

The collimated alpha particle source was then scanned across the bottom contact. A spectrum was acquired at each source location for each proximity electrode. A shaping time of 0.5 μs was used for this measurement. Fig. 5 shows how the centroid of the alpha particle peak varies across the detector. The centroids were normalized to the full-energy peak that would be obtained if the charge carriers were collected to an electrode on the detector surface. As expected, for each electrode, the peak centroid is at a maximum at the middle of the electrodes and decreases towards the edges. The data matches the calculated weighting potentials of the two electrodes. The good agreement indicates that the electric field in the detector was not distorted, meaning that the resistivity of the a-Si contact was low enough to prevent significant charging due to the bulk leakage current of the detector.
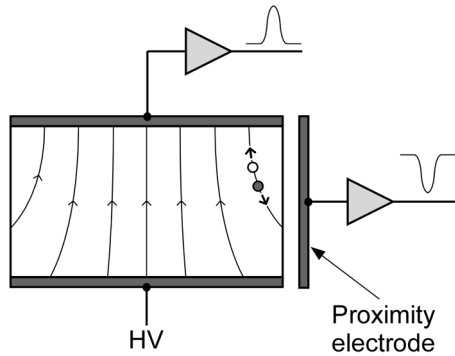
Fig. 6. Sensing incomplete charge collection on detector surface using proximity electrode.

Fig. 7. Ge detector with a wrap-around proximity electrode.

The experimental results demonstrate the proximity readout technique, and show that position-sensitive readout can be achieved using multiple proximity electrodes. In addition, position resolution can be greatly increased beyond that of the electrode pitch by interpolation based on the ratio of signal amplitudes obtained from adjacent proximity electrodes for each event. The amplitude ratio is given by the ratio of the weighting potentials of the electrodes at the location of charge collection on the surface of the detector.

IV. BACKGROUND REJECTION

Large-volume detectors, such as Ge detectors and CdZnTe detectors used for gamma-ray spectroscopy, and Si(Li) detectors for x-ray spectroscopy, can have detector thicknesses of up to several cm. The un-contacted side surfaces of these detectors, sometimes referred to as the intrinsic surfaces, can charge up and produce so-called surface channels. The bending of the internal field as a result of these surface channels can cause signal charges generated inside the detector to be collected at the surface instead of at the detector contacts, leading to incomplete charge collection and reduced signal amplitudes. This generates additional background in the spectra obtained with the detector.

Since the side surfaces of detectors are of necessity high resistivity, a proximity electrode placed close to the detector surface will produce an induced signal due to the collection of carriers within the detector, as shown in Fig. 6. For detectors that have negligible trapping of carriers in the bulk (e.g., Ge detectors), there will be no net charge induced at the proximity electrode as long as the carriers are fully collected at the detector's contacts. However, if some of the carriers are collected at the surface, a net induced signal is obtained. The carriers collected at the surface will slowly dissipate through surface conduction, and this will cause the induced charge signal to return to zero. This process, however, usually occurs at a much longer time scale than the typical shaping time so that effectively a net charge signal is observed at the proximity electrode. Therefore, a non-zero net induced charge signal at the proximity electrode can be used to indicate when incomplete charge collection occurs. The signals can then be used in anti-coincidence with the detector signals to reject surface collection events and reduce spectral background.

To demonstrate this, we performed measurements using a small planar Ge detector ($18 \text{ mm} \times 18 \text{ mm} \times 10 \text{ mm}$) with a proximity electrode wrapped around the detector close to the
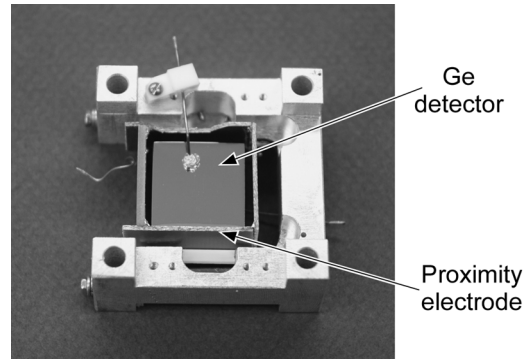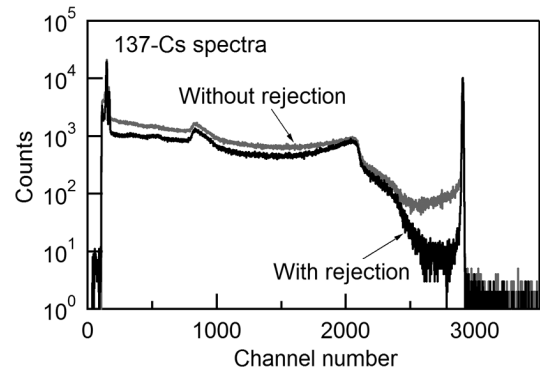

Fig. 8. Reduction in spectral background achieved by rejecting surface collection events in the Ge detector using signals from the proximity electrode.

side surfaces (Fig. 7). Fig. 8 shows the reduction in background achieved by using signals from the proximity electrode in anticoincidence with the detector signals. The two spectra were obtained for the same counting time without changing the source location. There is a loss in the photopeak counts of $\sim 1\%$ with anticoincidence. This is due to the fact that fully-collected events can induce transient signals at the proximity electrode. Although the net induced charge is zero, some of these transient signals can trigger the anticoincidence circuit, resulting in good events being rejected. It should be possible to reduce or eliminate such erroneously rejected events by devising a more effective circuit or signal processor to recognize the transient signals.

V. CONCLUSIONS

A method to sense charge collection in semiconductor detectors using proximity electrodes is introduced. The use of this technique for position-sensitive readout and background rejection has been demonstrated. By avoiding the need for hard-wired electrical connections between readout electronics and detectors, the detector fabrication and assembly can be greatly simplified. The proximity readout scheme also allows a simple method of position interpolation using the ratios of signal amplitudes from adjacent electrodes. By placing proximity electrodes near the side surfaces of conventional detectors, events with incomplete charge collection due to side surface collection can be sensed and rejected, resulting in the lowering of spectral background. It should also be possible to use the proximity electrode signals to determine the amount of charge loss and correct for it

in post processing. Similarly, this technique could in principle be applied to sense and correct for bulk carrier trapping as well.

REFERENCES

[1] G. Battistoni, E. Iarocci, G. Nicoletti, and L. Trasatti, "Detection of induced pulses in proportional wire devices with resistive cathodes," *Nucl. Instr. Meth.*, vol. 152, pp. 423–430, 1978.

[2] A. Athanasiades, J. L. Lacy, C. S. Martin, R. A. Austin, N. N. Shehad, and L. Sun, "Position sensing in a cylindrical ionization detector with a resistive cathode," *Nucl. Instr. Meth.*, vol. A505, pp. 252–255, 2003.

[3] P. N. Luke, M. Amman, T. H. Prettyman, P. A. Russo, and D. A. Close, "Electrode design for coplanar-grid detectors," *IEEE Trans. Nucl. Sci.*, vol. 44, no. 3, pp. 713–720, 1997.

[4] W. Shockley, "Currents to conductors induced by a moving point charge," *J. Appl. Phys.*, vol. 9, pp. 635–636, 1938.

[5] S. Ramo, "Current induced by electron motion," *Proc. IRE*, vol. 27, pp. 584–585, 1939.

[6] G. Battistoni, P. Campana, V. Chiarella, U. Denni, E. Iarocci, and G. Nicoletti, "Resistive cathode transparency," *Nucl. Instr. Meth.*, vol. 202, pp. 459–464, 1982.

[7] I. D. Hau, C. Tindall, and P. N. Luke, "New contact development for Si(Li) orthogonal-strip detectors," *Nucl. Instr. Meth.*, vol. A505, no. 1–2, pp. 148–154, 2003.

[8] M. Amman, P. N. Luke, and S. E. Boggs, "Amorphous-semiconductor-contact germanium-based detectors for gamma-ray imaging and spectroscopy," *Nucl. Instr. Meth. A*, vol. 579, p. 886, 2007.